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PLATING & SURFACE FINISHING, vol. 73, no. 5, 1980, pages 130-134; **C. OGDEN**: "High-strength, composite copper-nickel electrodeposits"

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JOURNAL OF THE ELECTROCHEMICAL SOCIETY, vol. 130, no. 10, October 1983, pages 1987-1994, Manchester, New Hampshire, US; **U. COHEN et al.**: "Electroplating of cyclic multilayered alloy (CMA) coatings"

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Description**BACKGROUND OF THE INVENTION**

5 The present invention relates to a new method for the production of composites possessing high elastic modulus and high magnetic properties by electrodeposition.

As known, electrodeposition (or electroplating) is defined as the art of production of metallic deposits through the motion of electric current on a solution containing the respective metal ion to be deposited. Such coatings have the purpose of improving the appearance, corrosion resistance, hardness, bearing
10 qualities or other properties of the basic metals, on which the coating is produced, or can be detached from the substrate and be used as tools in view of their special properties.

The technique of electroplating is widely used in many fields. There are specific cases such as springs, magnets or apparatus which require high or controlled modulus of elasticity or magnetism, when ordered alloys consisting of two or more metals in alternating layers up to 10 nm thickness will have to be
15 electrodeposited on a particular substrate. The use of the common electroplating techniques, i.e., the deposition of a layer of one metal in one bath followed by the electrodeposition of a second layer of another metal in another bath, may be conceived theoretically, but practically it is not applicable due to the long duration time which the operation of electrodeposition will involve and the complexity involved. The usual deposition of two metals from a common bath results in the production of alloys that are not ordered or
20 structured in discrete layers of the practically pure components of the objects to be coated, or the layers are not thin enough to acquire the necessary elastic or magnetic properties.

A few years ago, a proposal was made for obtaining composition modulated alloys or composites which possess the required properties of elasticity and magnetism, using the technique of vapor deposition (T. Tsakalakos et al., J. Physique C-7, 404, 1977). According to this method, composition modulated layers of
25 copper-nickel were prepared by co-evaporating the two components through a rotating pinwheel shutter onto a mica substrate at a temperature of 250 °C. But the method has various disadvantages, e.g. high cost of production and limitations in size and shape of the objects to be coated.

The essential parts of a typical electroplating system are:

- (1) the plating bath which contains a compound of the metal to be deposited;
- 30 (2) a source of direct current electricity;
- (3) the substrate to be coated; and
- (4) a counter electrode.

The negative terminal of the direct current source, is connected to the substrate (the cathode) while the positive terminal is connected to the counter electrode (the anode). When both of these electrodes are
35 immersed in the plating bath, oxidation occurs at the anode ions migrate to the cathode surface and are transformed to the metallic state and attached to that surface. The thickness of a plated coating is determined by the time of electroplating and the current density employed.

The pulse plating technique is a recognized method in the electroplating industry. The method consists in the turning on and off continuously in rapid succession the current applied to the electroplating bath.
40 During the pulse "on" time, the ions are electrodeposited out of solution at the cathode interface. During the pulse "off" time, the solution near the cathode interface becomes replenished with metal ions.

The technique of electrodeposition of two or more individual metals from one single solution, each metal to be deposited in a substantially pure form in such a way as to obtain enhanced modulus of elasticity and magnetism, was unknown prior to the present invention. The reason why such attempts could
45 not succeed, was explained by a thermodynamical assumption based on the fact that the noblest metal will deposit simultaneously with the less noble metal, or that the deposition of alternate layers at the required thickness was impossible by electrodeposition.

In a very recent paper by D. Tench and J. White (Metallurgical Transactions A. Vo. 15A, November 1984, p. 2039-40) composites of Ni-Cu layers are described which were electrodeposited from a bath
50 mentioning their enhanced tensile strength. The composites consisted actually of a rigid material (i.e. Ni) embedded in a soft matrix (i.e. Cu) like many known composites, and had neither enhanced modulus of elasticity nor any improved magnetic properties. Therefore, these composites could never be utilized for special applications requiring these properties.

In "Plating and Surface Finishing", Vol. 73, No. 5, 1980, Pages 130 to 134 a process for producing
55 macromodulated copper-nickel composite foils of enhanced mechanical properties is known. The composite is composed of several alternating layers of electrodeposited 100 % copper layers and ≥ 90 % nickel layers, the layers vary from 400 to 8 200 nm.

The J. Electrochemical Society 130, 1983, pages 1987 to 1993 describes the electroplating of Cyclic

Multilayered alloy coating composed of alternating Ag-rich and Pd-rich layers of a thickness in the range of 50 to 250 nm. It advises against forming layers of ≤ 10 nm with a lesser ion concentration in the electrolyte because an increase in erratic fluctuations in composition and morphology of the growth interface is to be expected.

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SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method for the production of compositions of modulated ordered alloys by electrodeposition. It is another object of the present invention to provide a simple method for the electrodeposition of at least two metals from solutions containing the respective metal salts possessing enhanced modulus of elasticity and magnetism. Thus, the invention consists in a method for the electrodeposition of an ordered alloy structured in alternate discrete layers of at least two metals from a solution containing the salts of the respective metals, said metals being characterized by a redox potential gap of at least 0.1 V between the noblest metal and the less noble one utilizing the pulse plating technique, with a frequency in the range of 0.02 to 15 Hz, wherein the concentration of the noblest metal present in said solution is in the range of 0.001 M to 1 M. It was found that by utilizing the pulse plating technique it is possible to work with a pulse current having a potential which will be positive enough to deposit the noblest metal but not the less noble metal followed by a pulse current with a more negative potential whereby substantially only the less noble metal will be deposited at which time the nobler metal deposition is restrained by a diffusion barrier. In this way it is possible to achieve a modulated electrodeposition of two distinct layers of the metals present in a solution wherein each discrete layer is less than 9 nm thick. The frequency of pulsing and the ratio of pulse durations are set at such a value as to produce layers of thickness in the orders of between 0.2 and 9 nm and preferably up to 5 nm each.

The concentration of the noblest metal in the solution, from which the modulated alloys are electrodeposited, should be in the range of 0.001 M to 1 M and preferably in the range of 0.005 M to 1 M. Concentrations below 0.001 M will require excessive time for the metal deposition, and this will not be practical from an economic point of view. On the other hand, the use of concentrations above 1 M will cause a simultaneous electrodeposition of the metals, i.e. one layer consisting of two or more metals. The concentration of the less noble metal is set as high as possible considering solubility data and maintaining the minimum potential gap mentioned above.

In the electrodeposition according to the present invention, layers are formed in thickness up to twenty times that of the crystal lattice parameter of the metal. The layers are alternately composed of the noblest metal and the less noble metals with a controlled level of presence of more noble metal in the layers of less noble metal according to the following equation:

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$$P_m = \frac{I_L}{I_T \cdot \eta}$$

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wherein

P_m = the concentration of the noblest metal in the area of less noble metal expressed in % gram equivalent;
 I_L = the limiting current density for the noblest metal electrodeposition depending on metal concentration and agitation
 I_T = the total current density applied during the electrodeposition of the less noble metal layer; and
 η = cathodic efficiency.

When the ratio I_L/I_T is much less than 1, the P_m tends toward zero, which means that the less noble metal layer can be formed practically pure.

The anions of the metal salts in the bath from which the electrochemically modulated structure is deposited may be selected from the common anions used for this technique in electrochemical processes. Examples of particular anions are: sulfate, sulfamate, pyrophosphate, cyanide and chloride. The known additives generally utilized in the electrodeposition of a metal, such as ammonium tartrate ammonia (as buffer) or pyrophosphates, and surface active agents, such as dodecyl sulfate, will also be desirable to be incorporated.

The pH suitable for the electrodeposition according to the present invention may be in a broad range, preferably being above 1. At a pH below 1, the method would still be applicable but a low deposition

efficiency will result due to excessive hydrogen evolution. The most preferred pH range is between 2 and 3.

The temperature which prevails during the electrodeposition according to the present invention, is that normally utilized in the usual electrodeposition, ranging from 25° to 90° C. It was found that an increase in temperature will cause a decrease in the concentration of the noblest metal electrodeposition at high current densities.

According to a most preferred embodiment, agitation is carried out during the electrodeposition of the noblest metal, and towards the end of its deposition the agitation is stopped and the electrodeposition of the less noble metal is carried out without any agitation. In this manner, the degree of purity of the metal layers deposited will be highest possible. As known from the electroplating technique, the agitation assists to obtain uniform conditions and results in achieving high rates of deposition. The process can also be performed without agitation but will then require a longer deposition time.

Among the most preferred metals to be electrodeposited the following are mentioned: copper and nickel, copper and palladium, nickel-gold, copper-nickel-iron and corresponding alloys with cobalt or iron replacing nickel. All the above combinations of metals are characterized by a gap of a potential of at least 0.1 V between the noblest metal and the less noble metal which is one of the requirements of the present method.

One of the critical parameters found to be required according to the present invention, is the concentration of the noblest metal in the solution to be in the range of 0.001 M to 1 M and preferably in the range of between 0.005 M to 1 M. At this concentration, the limiting current density is low enough to ensure dilution of this metal in the layers of the other metal so that the latter can be produced practically pure. The concentration of the less noble metal is set at high as practicable to obtain the desired layer thickness, being preferably near the saturation.

The frequency utilized in the electrodeposition operation should be between 0.02 and 15 Hz and preferably in the range of between 0.15 to 2 Hz. The potential is pulsed at this frequency between a value which is selected so to be between the redox potentials of the two metals and a second value which is selected so as to be substantially more negative than that of the less noble metal. The ratio of pulse durations is determined by the desired layer thickness as related to the electrical charge passed during each pulse. The pulsing can alternatively be done by current control if the relationship between electrode potential and current density is previously determined.

The present invention is applicable for the production of metal alloy sheets or rods or any other desired form combined of two or more metals which are structured as discrete layers of the substantially pure components, and in particular to layers with thicknesses which vary from 0.2 to 9 nm and preferably between 1 and 5 nm. The total thickness of the formed alloy is optional. The layers of the metals which are electrodeposited are substantially pure, and form integral and coherent structure of unique properties such as high modulus of elasticity, high and adjustable magnetic susceptibility and excellent corrosion resistance especially against pitting and other types of localized attack.

It was found that the modulated structure of compositional modulated ordered alloys such as those produced according to the present invention causes an increase in the elastic modulus, compared with the homogeneous alloys. This increase depends on several parameters:

- (a) wavelength of the modulation;
- (b) average composition of the alloy; and
- (c) modulation's amplitude.

The elastic modulus was measured by bulge testing on Cu-Ni thin films containing short wavelength composition modulation and was compared to that of pure copper specimens and homogeneous alloys of Cu-Ni. The following results illustrate the improved properties of compositional modulated thin films.

The elastic modulus (Y) of pure copper specimen is:

$$Y = 179\,400 \text{ N/cm}^2 \text{ (0.26 Tpa, 1 Tpa} = 690\,000 \text{ N/cm}^2)$$

for homogeneous Cu-Ni specimen:

$$Y = 227\,700 \text{ N/cm}^2 \text{ (0.33 Tpa)}.$$

The elastic modulus for the composition modulated alloy such as produced according to the present invention, obtained at a wavelength of 1.7 nm containing 45 % Cu, was $Y = 600\,300 \text{ N/cm}^2$ (0.87 Tpa).

The magnetization density (M) of modulated Cu-Ni thin films, obtained at a wavelength of 3 nm, was produced from ferromagnetic resonance data. It was found that M increased as the temperature decreases. At 125 K, M is significantly greater than that of pure Ni. For modular Cu-Ni foils that have been annealed to a homogeneous alloy, it was found that M decreased by an order of magnitude which indicates that the modulation contributes to the magnetization density.

According to another embodiment, a very thin foil of Ni (about 20 nm) is attached to a magnetic electrode and immersed in a plating bath containing a solution consisting of Cu and Ni. The modulated

deposit of Cu-Ni built onto the foil, to approximate 0.3 μm thickness, possesses magnetic properties and could be easily detached as a foil product. Furthermore, the magnetic properties could be tailored to desired levels by controlling the level of alloying of the less noble metal layers or the total alloy content.

Thus the following Examples which include preferred embodiments will serve to illustrate the practice of this invention, it being understood that the particulars described are by way of examples and for purposes of illustrating discussion of preferred embodiments of the present invention only and are presented to provide what is believed to be the most useful and most readily understood description of the procedure as well as of the principles and conceptual aspects of the invention.

10 EXAMPLE 1

Into an electroplating bath connected to a pulsed current, the following solutions were introduced:

330 g/l	$\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$
45 g/l	$\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$
35 g/l	H_3BO_3
0.4 g/l	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$

The temperature of the bath was kept at about 30°C, the pH being between 2 to 3. The frequency was 0.16 Hz at a ratio $1:8 \times 10^{-3}$ between -0.4 and -1.12 V on the calomel scale. The thickness of each layer was 1.7 nm, the total thickness being about 1 μm . The total time for the above electrodeposition was about 25 min. The foil obtained will have an elasticity modulus of above 250 % greater than the homogeneous alloy with the same average composition.

25 EXAMPLE 2

The same experiment as above was repeated. The bath composition was as follows:

330 g/l	$\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$
45 g/l	$\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$
35 g/l	H_3BO_3
3 g/l	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$

Sodium dodecyl sulfate and coumarine: 0.1 g/l each. Strong agitation was employed only during the copper deposition. Alternate potentiostatic pulses of -0.2 V and -1.7 V on the normal hydrogen scale (or alternatively galvanostatic current pulses of -5 mA/cm² and -200 mA/cm²) were imposed. The frequency was 1 Hz at a ration of 1:0.025 respectively.

40 Claims

1. A method for the electrodeposition of a composite foil consisting of substantially pure layers of one metal alternating with substantially pure layers of another metal each layer having a thickness of less than 9 nm,

A) by electrolysing a bath

a) comprising a solution of two metals chosen such that the redox potential gap between the more noble metal and the less noble metal is at least 0.1 V,

b) wherein the concentration of the more noble metal ion is in the range of 0.001 to 1.0 M and

c) the concentration of the less noble metal ion is near the level of saturation thereof at room temperature;

B) applying a frequency between 0.02 Hz and 15 Hz and a potential to the cathode at a first value which is selected so as to be between the potentials at which the metals begin to deposit under the conditions used, for a sufficient time to deposit less than 9 nm - preferably 0.2 to 5 nm - thickness of substantially pure more noble metal;

C) changing the potential applied to the cathode to a second value which is selected so as to be substantially more negative than the potential at which the less noble metal begins to deposit under the conditions used, the potential being increased until the total current density is higher than the

limiting current density for the more noble metal so that the percentage of more noble metal in the less noble metal layer approaches zero, thereby permitting deposition of substantially pure less noble metal, the potential being applied for a sufficient time to deposit less than 9 nm - preferably 0.2 to 5 nm - thickness of the substantially pure less noble metal; and

D) repeating step B.) and C.) for a predetermined number of cycles to obtain a corresponding number of layers of the metals.

2. The method in accordance with claim 1, wherein the frequency utilized in the electrodeposition operation is in the range of between 0,15 Hz to 2 Hz.

3. The method in accordance with claim 1 or 2, wherein the anions, in the bath, of the metals to be electrodeposited are selected from sulfate, sulfamate, pyrophosphate, cyanide and chloride.

4. The method in accordance with claims 1 to 3, wherein the pH during the electrodeposition is maintained above 1, preferably between 2 and 3.

5. The method in accordance with claims 1 to 4, wherein the temperature during the electrodeposition is maintained in the range of 25-90 ° C.

6. The method in accordance with claims 1 to 5, wherein the bath is agitated during the electrodeposition.

7. The method in accordance with claims 1 to 5, wherein the bath is agitated only during the step C.) of depositing the substantially pure more noble metal.

Patentansprüche

1. Verfahren zur elektrochemischen Ablagerung einer zusammengesetzten Folie, die aus im wesentlichen reinen Schichten eines Metalls abwechselnd mit im wesentlichen reinen Schichten eines anderen Metalls besteht, wobei jede Schicht eine Dicke von weniger als 9 nm hat,

A) durch Elektrolysieren eines Bades

a) welches eine Lösung aus zwei Metallen aufweist, die so gewählt sind, daß die Redoxpotential-lücke zwischen dem edleren Metall und dem weniger edlen Metall mindestens 0,1 V beträgt,

b) worin die Konzentration des edleren Metallions im Bereich von 0,001 bis 1,0 M liegt und

c) die Konzentration des weniger edlen Metallions in der Nähe des Sättigungsniveaus desselben bei Zimmertemperatur liegt;

B) Anlegen einer Frequenz zwischen 0,02 Hz und 15 Hz und eines Potentials an die Kathode bei einem ersten Wert, der so gewählt ist, daß er zwischen den Potentialen liegt, bei denen die Metalle sich unter den angewandten Bedingungen abzulagern beginnen, während einer ausreichenden Zeit zum Niederschlag von weniger als 9 nm - vorzugsweise 0,2 bis 5 nm - Dicke aus im wesentlichen reinem, edleren Metall;

C) Ändern des an die Kathode angelegten Potentials auf einen zweiten Wert, der so gewählt ist, daß er im wesentlichen negativer ist als das Potential, bei dem das weniger edle Metall sich unter den angewandten Bedingungen abzulagern beginnt, wobei das Potential erhöht wird, bis die Gesamtstromdichte höher ist als die Grenzstromdichte für das edlere Metall, so daß der Prozentsatz an edlerem Metall in der Schicht aus weniger edlem Metall sich Null nähert, was das Abscheiden im wesentlichen reinen, weniger edlen Metalls erlaubt, wobei das Potential während einer ausreichenden Zeit angelegt wird, um weniger als 9 nm - vorzugsweise 0,2 bis 5 nm - Dicke des im wesentlichen reinen, weniger edlen Metalls abzulagern; und

D) Wiederholen von Schritt B) und C) für eine vorherbestimmte Anzahl von Zyklen zum Erhalten einer entsprechenden Anzahl von Schichten der Metalle.

2. Verfahren nach Anspruch 1, bei dem die für den Galvanisiervorgang benutzte Frequenz im Bereich zwischen 0,15 Hz bis 2 Hz liegt.

3. Verfahren nach Anspruch 1 oder 2, bei dem in dem Bad die Anionen der elektrochemisch abzuscheidenden Metalle aus Sulfat, Sulfamat, Pyrophosphat, Cyanid und Chlorid ausgewählt werden.

4. Verfahren nach Anspruch 1 bis 3, bei dem der pH-Wert während der Galvanisierung oberhalb 1,

vorzugsweise zwischen 2 und 3 gehalten wird.

5. Verfahren nach Anspruch 1 bis 4, bei dem die Temperatur während des Galvanisierens im Bereich von 25 bis 90 ° C gehalten wird.

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6. Verfahren nach Anspruch 1 bis 5, bei dem das Bad während des Galvanisierens gerührt wird.

7. Verfahren nach Anspruch 1 bis 5, dadurch gekennzeichnet, daß das Bad nur während des Schritts C) der Ablagerung des im wesentlichen reinen, edleren Metalls gerührt wird.

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Revendications

1. Procédé d'électrodéposition d'une feuille composite comprenant des couches à peu près pures d'un métal en alternance avec des couches à peu près pures d'un autre métal, chaque couche ayant une épaisseur de moins de 9 nm;

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A) par électrolyse d'un bain:

a) comprenant une solution de deux métaux choisis de telle sorte que l'intervalle de potentiel rédox entre le métal le plus noble et le métal le moins noble, soit d'au moins 0,1 V,

b) dont la concentration en le métal le plus noble, est de 0,001 à 1,0 M, et

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c) la concentration en l'ion de métal le plus noble, étant voisine de sa concentration saturante à la température ambiante;

B) en appliquant à la cathode, une fréquence de 0,02 Hz à 15 Hz et un potentiel à une première valeur choisie de façon à être entre les potentiels auxquels les métaux commencent à être déposés dans les conditions employées, pendant un temps suffisant pour déposer moins de 9 nm, de préférence de 0,2 à 5 nm, d'épaisseur du métal le plus noble à peu près pur;

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C) en modifiant le potentiel appliqué à la cathode, jusqu'à une deuxième valeur choisie de façon à ce qu'il soit nettement plus négatif que le potentiel auquel le métal le moins noble commence à se déposer dans les conditions employées, le potentiel étant accru jusqu'à ce que la densité de courant totale soit supérieure à la densité de courant limite du métal le plus noble, de telle sorte que le pourcentage du métal le plus noble soit voisin de zéro dans la couche de métal le moins noble, pour permettre ainsi le dépôt de métal le moins noble à peu près pur, le potentiel étant appliqué pendant un temps suffisant pour déposer moins de 9 nm, de préférence de 0,2 à 5 nm, d'épaisseur du métal le moins noble à peu près pur; et

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D) en répétant les étapes B) et C) un nombre prédéterminé de cycles, de façon à obtenir un nombre correspondant de couches des métaux.

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2. Procédé selon la revendication 1, dans lequel la fréquence utilisée dans l'opération d'électrodéposition, est de 0,15 Hz à 2 Hz.

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3. Procédé selon la revendication 1 ou 2, dans lequel les anions présents dans le bain des métaux destinés à être déposés par électrolyse, sont choisis parmi les anions sulfate, sulfamate, pyrophosphate, cyanure et chlorure;

4. Procédé selon les revendications 1 à 3, dans lequel le pH au cours de l'électrodéposition, est maintenu au-dessus de 1, de préférence de 2 à 3.

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5. Procédé selon les revendications 1 à 4, dans lequel la température au cours de l'électrodéposition, est maintenue dans la plage de 25 à 90 ° C.

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6. Procédé selon les revendications 1 à 5, dans lequel le bain est agité au cours de l'électrodéposition.

7. Procédé selon les revendications 1 à 5, dans lequel le bain est agité seulement au cours de l'étape C) de dépôt du métal le plus noble à peu près pur.

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